ACTIVITY AT THE DEUTERIUM-BURNING MASS LIMIT IN ORION

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ABSTRACT

We report very intense and variable Hα emission (pseudo-equivalent widths of $\sim$ 180, 410 Å) of S Ori 55, a probable free-floating, M9-type substellar member of the young σ Orionis open star cluster. After comparison with state-of-the-art evolutionary models, we infer that S Ori 55 is near or below the cluster deuterium-burning mass borderline, which separates brown dwarfs and planetary-mass objects. We find its mass to be 0.008–0.015 $M_\odot$ for ages between 1 Myr and 8 Myr, with $\sim$0.012 $M_\odot$ the most likely value at the cluster age of 3 Myr. The largest Hα intensity reached the saturation level of $\log L_{\mathrm{H}\alpha}/L_{\mathrm{bol}} = -3$. We discuss several possible scenarios for such a strong emission. We also show that σ Orionis M and L dwarfs have in general more Hα emission than their older field spectral counterparts. This could be due to a decline in the strength of the magnetic field with age in brown dwarfs and isolated planetary-mass objects, or to a likely mass accretion from disks in the very young σ Orionis substellar members.

Subject headings: stars: activity — stars: individual (S Ori 55) — stars: low mass, brown dwarfs — stars: pre-main sequence — open clusters and associations: individual (σ Orionis)

1. INTRODUCTION

Since the discovery of substellar objects (unable to fuse hydrogen stably in their interiors and with masses below 0.072 $M_\odot$, Kumar (1963); Chabrier et al. (2000a)), many efforts have been devoted to their characterization (see Basri (2000) for a review). Recently, Muench et al. (2001) found evidence for the presence of disks around brown dwarfs (BDs) of the Trapezium cluster. Muzerolle et al. (2000) and Martín et al. (2001) reported on disk accretion in T Tauri objects with masses near the substellar borderline. All these works may suggest that "circumstellar" disks are common among very young BDs. These objects generally show Hα in emission, which seems to be variable. To the best of our knowledge, only a few BDs with masses larger than 0.06 $M_\odot$ have been observed flaring (Rutledge et al. (2000); Basri & Martín (1999)).

Here, we report on the detection of strong Hα emission in S Ori 55 (S Ori J053725.9–023432), which was previously identified as a cool, very low mass substellar member of the young σ Orionis open cluster (Zapatero Osorio et al. (2000); Barrado y Navascués et al. (2001)). Table 1 summarizes available spectrophotometric data for this object.

2. OBSERVATIONS AND RESULTS

We acquired low-resolution optical spectra of S Ori 55 with the red module of the Low-Resolution Imaging Spectrograph (Oke et al. (1995)) at the 10-m Keck I telescope (Mauna Kea Observatory) on 2001 January 31. We used the 2048$\times$2048 pixel SITE detector (0.25$''$ pix^{-1}), the 150 lines mm^{-1} grating blazed at 750.0 nm, the OG570 filter for blocking the light blueward of 570.0 nm, and a 1.5$''$-width slit, which provides a wavelength coverage of 600–1030 nm, a spectral nominal dispersion of 4.0 Å pix^{-1} and a final resolution of 24 Å ($R \sim 350$). The slit was rotated to be at a parallactic angle and minimize refraction losses. Two individual exposures of 2400 s each were obtained at different positions separated by 6$''$ along the entrance slit. Weather conditions were spectrophotometric, with seeing around 1.5$''$. Raw images were processed with standard

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techniques that include bias subtraction and flat-fielding within IRAF[2]. Nodded images were subtracted to remove Earth's atmospheric contribution. A full-wavelength solution (the *rms* of the fifth-order polynomial fit was 1 Å) was achieved by calibrating sky emission lines as in Osterbrock et al. (1996). To complete data reduction, we corrected for the instrumental response using data of the spectrophotometric standard star G 191–B2B obtained on the same night and with the same instrumental configuration.

The resultant combined spectrum of S Ori 55 is depicted in Figure 1 (S/N∼10 at 750 nm, and S/N∼15 at 905 nm). The spectra of the σ Orionis substellar member S Ori 47 (L1.5, Zapatero Osorio et al. (1999)) and the field dwarf PC 0025+0447 (M9.5, Kirkpatrick, Henry, & Simons (1995)) are also shown for comparison. We derived the spectral type of our target by matching its observed spectrum to data of standards, which were previously obtained with similar instrumentation. We also used the PC3 index of Martín, Rebolo, & Zapatero Osorio (1996). We measured an M9 spectral class with an uncertainty of half a subclass, in full agreement with the previous assignement of Barrado y Navascués et al. (2001) and with the observed IJK colors. Interestingly, S Ori 55 displays typical low-gravity features (Allard et al. (2001); Martín et al. (1996); Luhman, Liebert, & Rieke (1997); Béjar, Zapatero Osorio, & Rebolo (1999)), such as the absence of Na I $\lambda\lambda$818.3, 819.5 nm, and K I $\lambda\lambda$762.1, 766.7 nm atomic lines at the resolution of our data, and stronger molecular absorptions of VO and TiO compared to field spectral counterparts. Our measured upper limits to the line pseudo-equivalent widths (pEWs, relative to the local observed pseudo-continuum formed by molecular absorptions) are given in Table 1. These values are significantly smaller than those of older objects in the Pleiades and the field (Martín et al. (1996); Zapatero Osorio et al. (1997)).

The Keck optical data of S Ori 55 show a rather strong Hα line, which is seen in emission and with a different intensity between the two closely spaced spectra. A close-up region around Hα is displayed in Figure 2. S Ori 55 appears very active; however we found the same spectral type as Barrado y Navascués et al. (2001), suggesting that no significant continuum veiling of the visible photospheric features is present in the Keck spectra. Measuring Hα pEWs is not easy because the number of counts at the line pedestal is small (50–140 counts). In Table 1 we provide heliocentric Julian dates and our best pEW measurements obtained via direct integration of the line profile adopting the pseudo-continuum level immediately adjacent to the line (around λ652.5 and λ664.0 nm). The error bars were obtained after integrating over a reasonable range of possible continua. We are confident that the emission is larger in the second Keck spectrum than in the first one, which was taken 43 minutes earlier. Barrado y Navascués et al. (2001) found a less intense emission (pEW = 5 Å) in their VLT optical data taken ∼1 month before the Keck observations. This result and our observations indicate that S Ori 55 has a variable Hα emission.

Spectroscopy, and optical and near-IR photometry are all consistent with S Ori 55's being a member of the σ Orionis cluster. But late-M stars are also common in the galactic disk, so we have considered the probability that S Ori 55 might simply be an interloper field M9 dwarf in the direction toward the cluster (lying at a distance between 118 pc and 197 pc in a volume of roughly 142 pc^3). For this exercise we have used three-band photometry and the absolute magnitudes of field stars (Leggett et al. (2002)). Very recent all-sky surveys show that the space density of M8–M9.5 dwarfs per cubic parsec is 0.0045 ± 0.0008 (Gizis et al. (2000)). In our survey of the σ Orionis cluster (Zapatero Osorio et al. (2000)), we found five candidates (including S Ori 55) with M9–M9.5 spectral types in an interval of roughly 1 mag (Barrado y Navascués et al. (2001)). The probability of each candidate being a true member is in the range 87–93%. The finding of such a large number of cool M dwarfs in our survey can be understood in terms of the much higher object density in the σ Orionis cluster than in the field.

3. MASS DETERMINATION

The very likely membership of S Ori 55 in the σ Orionis cluster allows us to derive its mass by comparison with state-of-the-art evolutionary models. Its effective temperature ($T_{\rm eff}$) can be inferred from the spectral type and the optical-infrared colors. The calibration of Basri et al. (2000) gives $T_{\rm eff} = 2370$ K for an M9 dwarf, while Luhman's (1999) scale, which is intermediate between dwarfs and giants, provides $T_{\rm eff} = 2550$ K. Recently, Béjar (2001) has derived a temperature calibration by matching observed low-resolution optical spectra of cluster M-type BDs to a spectral synthesis computed for the dusty, $\log g = 3.5$ model atmospheres of Allard et al. (2001) (see Pavlenko, Zapatero Osorio, & Rebolo (2000)). Béjar (2001) found $T_{\rm eff} = 2500$ K for an M8.5 cluster member. Because S Ori 55 has a surface gravity around $\log g = 4.0$, on the basis of theoretical models, its $T_{\rm eff}$ could be in the range 2370–2550 K. Less uncertainties exist in the calculation of the bolometric luminosity. Using the photometry of S Ori 55 and the bolometric corrections of Monet et al. (1992), Reid et al. (2001), and Leggett et al. (2002), we derived $\log L/L_\odot = -3.08 \pm 0.25$. The uncertainty is mainly due to the error in the Hipparcos distance (Perryman et al. (1997)) to the massive central star of the cluster.

Figure 3 illustrates the substellar mass-luminosity relationships of Chabrier et al. (2000a) and Burrows et al. (1997). These two sets of evolutionary models deal with dusty atmospheres differently. While the former models assume that dust particles are formed in the atmosphere and remain there impacting the output energy distribution, the latter models treat dust as if condensed below the photosphere. S Ori 55 may be coeval with other cluster members; thus its mass can be easily deduced from the figure. The age of the σ Orionis association is discussed to some extent in Zapatero Osorio et al. (2002). These authors concluded that the most likely cluster age is 2–4 Myr, although ages as young as 1 Myr and as old as 8 Myr cannot be discarded. Further discussion of other cluster properties can be found in Béjar et al. (2001) and Walter, Wolk, & Sherry (1998). In Figure 3 the vertical lines between $0.012 M_\odot$ (Chabrier et al. (2000b)) and $0.015 M_\odot$ (Bur-

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[2] IRAF is distributed by National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

rows, Hubbard, & Lunine (1989)) denote the deuterium-burning mass limit, which separates BDs and planetary-mass objects. Values as high as $0.018\,M_\odot$ can be found in the literature (D'Antona & Mazzitelli (1994)). The luminosity of S Ori 55, its error bar, and possible ages are indicated with the region enclosed by the thick line. The filled circle stands for the most likely values of luminosity and age. Using the Chabrier et al. (2000a) models, the mass of S Ori 55 is estimated at $0.012 \pm 0.004\,M_\odot$, i.e., very close to the deuterium-burning mass threshold. The tracks of Burrows et al. (1997) yield smaller masses by $\sim$10%. S Ori 55 is defining the cluster frontier between BDs and planetary-mass objects. It could be a planetary-mass cluster member if it were younger than $\sim$3 Myr.

4. DISCUSSION AND FINAL REMARKS

This is the first time that very large Hα emission has been detected in a low mass substellar object. Its origin remains unknown. S Ori 55 may simply have undergone a chromospheric flare due to magnetic activity. This is supported by the rapid time variability of the line and the lack of a constant, significant emission. Furthermore, no additional continuum appears to be veiling the photospheric spectral features. Many dwarfs at the bottom of the M class experience strong and weak flares (Gizis et al. (2000); Martín & Ardila (2001)). Based on our data, we tentatively estimate that the flaring recurrence of S Ori 55 is about 33–66%, which contrasts with the 7% value of the field coolest M dwarfs (Gizis et al. (2000)).

Similarly intense Hα lines have been detected in just a few field objects of related $T_{\rm eff}$. Liebert et al. (1999) observed a strong flare in 2MASSW J0149090+295613 (M9.5) with Hα pEWs of 200–300 Å, and many other emission lines of He I, O I, K I and Ca II. Mould et al. (1994) and Martín, Basri, & Zapatero Osorio (1999) reported variable and persistent Hα emission in PC 0025+0447 (M9.5) with pEWs between 100 and 400 Å. Liebert et al. interpreted the behavior of the 2MASS object as that of a very cool M-type flare star, and they pointed out that this flare activity differs from that of PC 0025+0447. Albeit with differences, the optical spectra of PC 0025+0447 and S Ori 55 seem more alike. Burgasser et al. (2000) argued that the former object could be an interacting binary. S Ori 55 might also be double with one of the components losing mass to the other. Our optical spectra do not suggest the presence of a warm component or a significant variation of the continuum over a month. ROSAT X-ray data provide an upper limit of $\log\,(L_X/L_{\rm bol}) \le -0.9$ to the X-ray emission of S Ori 55 (Mokler (2002)). We note, however, that PC 0025+0447 does not show significant X-ray flux (Neuhäuser et al. (1999)).

The strong Hα emission of S Ori 55 may have its origin in the object formation processes. Haisch, Lada, & Lada (2001) found that the presence of dusty disks surrounding stellar members of clusters as young as the σ Orionis cluster is significantly high (50%–65%). There are also clear indications of accretion events among the low mass star population of σ Orionis (Zapatero Osorio et al. (2002)). However, accreting T Tauri stars show continuous strong emission, whereas S Ori 55 appears to have episodes of low and high activity. It could be that mass infall from protoplanetary disks onto central substellar-mass objects turns out to be unstable due to nonuniform disks and variable magnetic fields. Sporadic accretion events may also indicate the end of the accreting activity in BDs and planetary-mass objects. The mass infall rate seems to be rather small in objects around the substellar limit (Muzerolle et al. (2000)). S Ori 55 does not show an infrared excess in the K band, which is consistent with a very low accretion rate. With current data we cannot rule out any possible scenario (flare activity, binarity, mass accretion).

We have compared the Hα emission to the bolometric luminosity ($L_{\rm bol}$) of σ Orionis low mass members from the late-K spectral type (stellar regime) down to mid-L classes (planetary-mass domain). Hα fluxes ($L_{\rm H\alpha}$) have been calculated as in Herbst & Miller (1989), and bolometric corrections have been taken from various sources in the literature (Monet et al. (1992); Leggett et al. (2002)). Our results are portrayed in Figure 4. For comparison purposes, we have also included the averaged values of field stars with similar spectral types (individual star data published by Hawley, Gizis, & Reid (1996), and Gizis et al. (2000)). The three observations of S Ori 55 are clearly indicated. The ratio $L_{\rm H\alpha}/L_{\rm bol}$ of cluster members with warm spectral types down to mid- and late-M classes appears to be rather dispersed around $\log L_{\rm H\alpha}/L_{\rm bol} = -3.61$ dex (Zapatero Osorio et al. (2002)). Cooler types (corresponding to planetary-mass objects) display a less intense ratio by about 0.6 dex, which implies a decrease in the activity level (less intense magnetic fields). On average, σ Orionis members, and remarkably those in the L classes, show higher Hα emissions than their older, field spectral counterparts. This feature could be explained partly as a decline in the strength of the chromospheric and flare activity with age and/or mass accretion from surrounding disks in the young objects. This would indicate that magnetospheric mass infall could extend even beyond the deuterium-burning mass threshold, i.e., into the planetary-mass domain.

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TABLE 1

DATA FOR S ORI 55 (S ORI J053725.9–023432).

I	$I-J$	$I-K$	SpT	$T_{\rm eff}$	$\log L/L_\odot$	$M/M_\odot$	HJD[a]	Hα[b]	Na I[b]	K I[b]
21.32±0.03	3.10±0.07	4.32±0.10	M9±0.5	2370–2550	–3.08±0.25	0.012±0.004	6.7211	5±5		
							41.8093	180±80	≤2	≤16
							41.8390	410±100	≤2	≤16

[a]HJD – 2451900 (beginning of the exposures).

[b]Pseudo-equivalent widths in Å (see text).

Note. — Photometric magnitudes taken from Zapatero Osorio et al. (2000). $T_{\rm eff}$ is given in K. The first Hα pEW is taken from Barrado y Navascués et al. (2001).
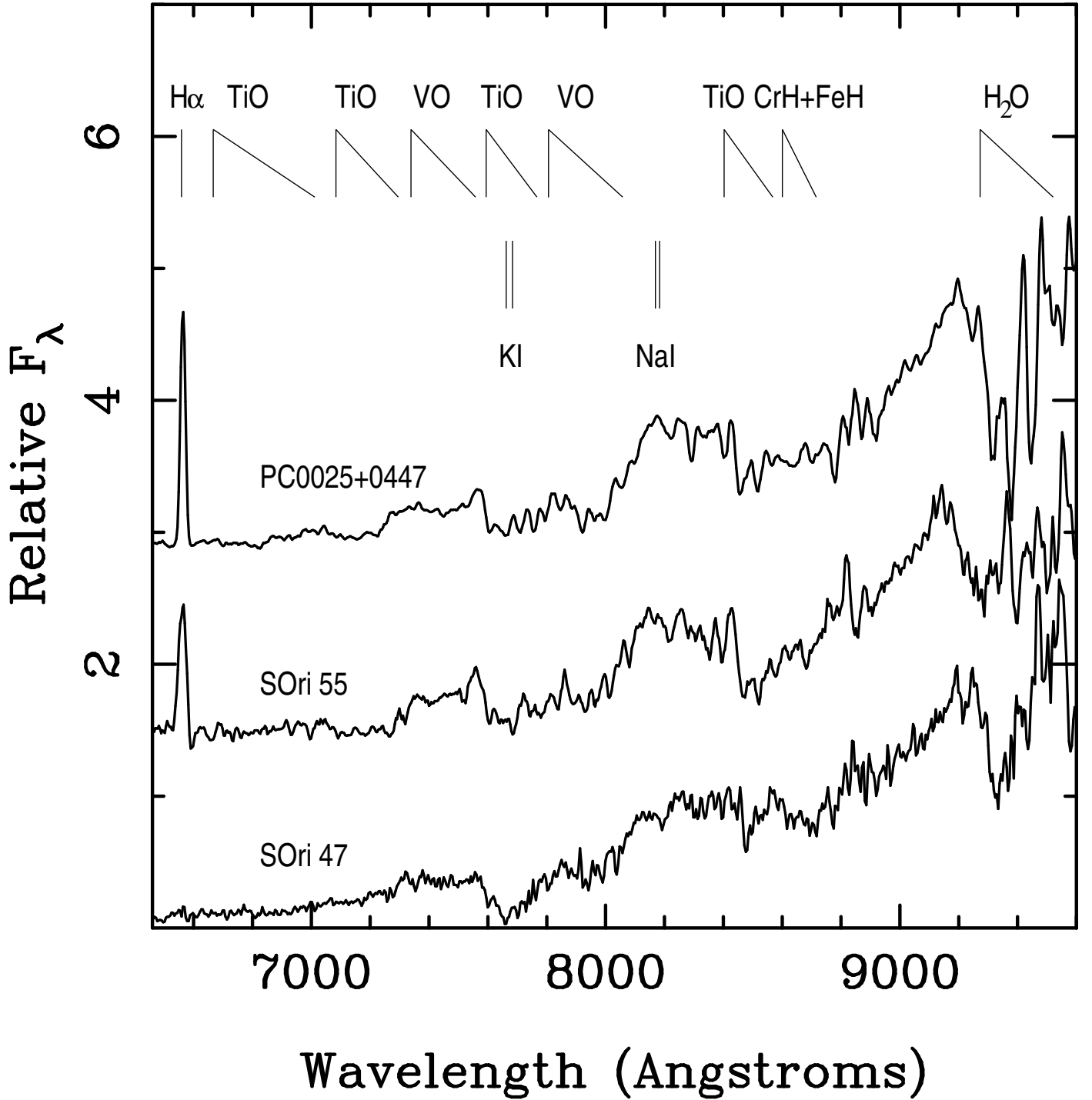
FIG. 1.— Keck low-resolution averaged spectrum of S Ori 55 (M9). S Ori 47 (L1.5, another substellar member of the σ Orionis cluster) and the field dwarf PC 0025+0447 (M9.5) are also shown for comparison (spectra taken from Martín et al. (1999)). A boxcar smoothing of 5 pixels has been applied to the data of S Ori 55 and PC 0025+0047. All spectra are normalized to the counts at $\sim$8150 Å. Upper spectra are shifted by 1.4 units each for clarity. Main molecular and atomic features are indicated as in Kirkpatrick et al. (1999).
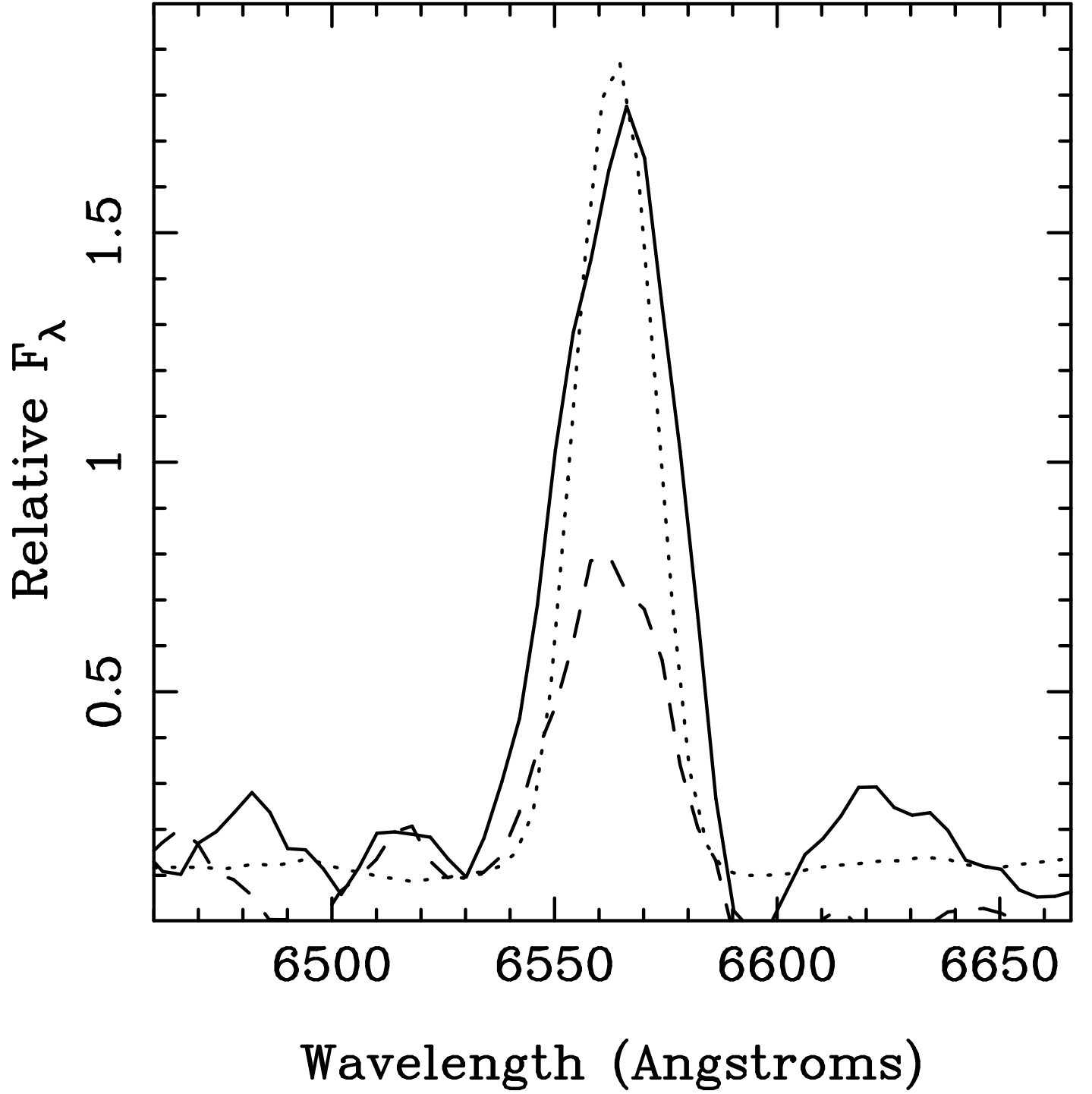
FIG. 2.— Hα profiles of S Ori 55 (first spectrum—dashed line; second spectrum—solid line). PC 0025+0447 (dotted line) is included for comparison (same spectral resolution). Observed fluxes are normalized as in Fig. 1.
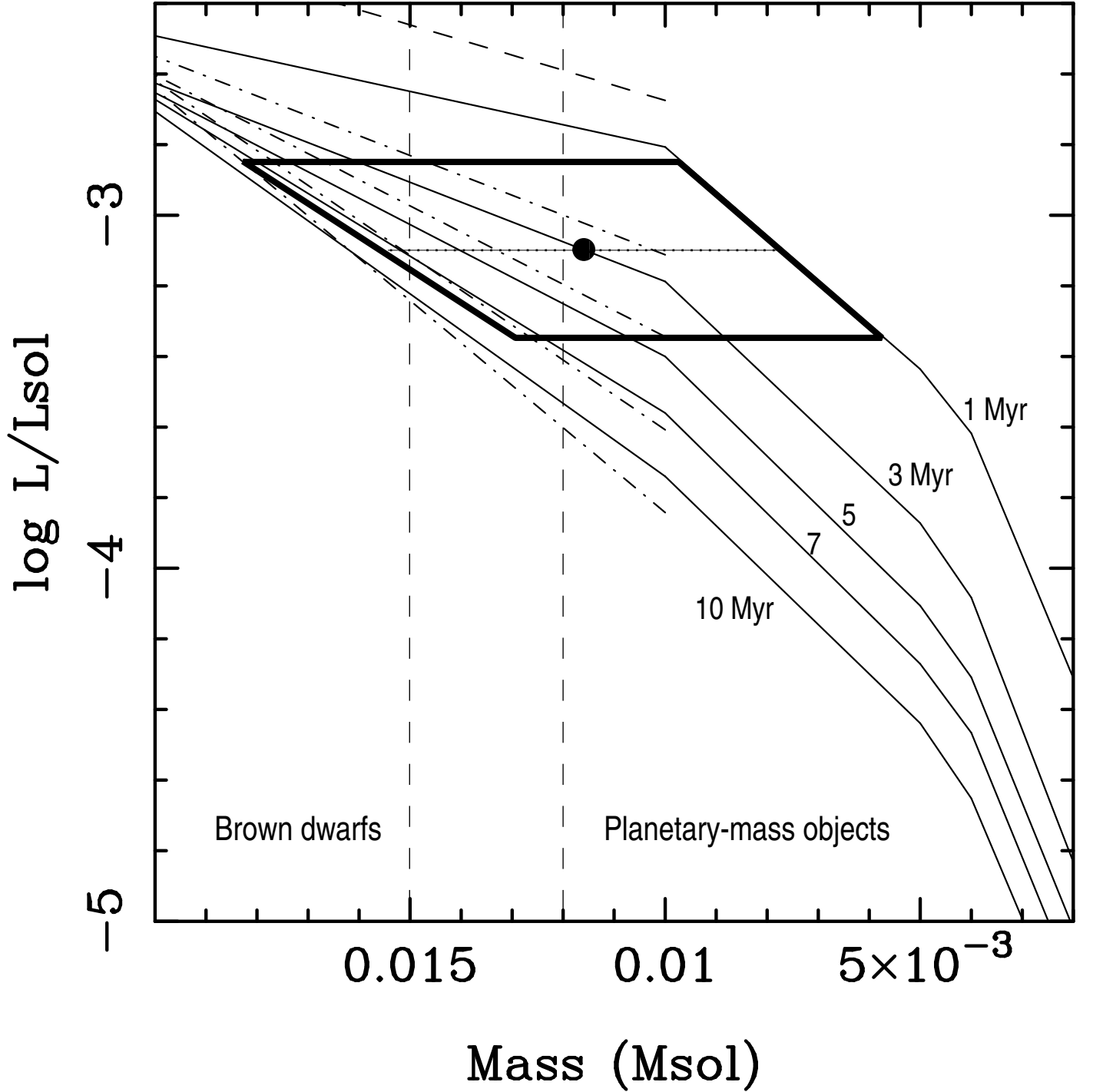
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Fig. 3.— Mass of S Ori 55. Models (1–10 Myr) of Chabrier et al. (2000a) and Burrows et al. (1997) are plotted with solid and dash-dotted lines, respectively. Vertical dashed lines indicate the deuterium-burning mass limit (borderline between brown dwarfs and planetary-mass objects; Saumon et al. (1996)). The age of S Ori 55 is believed to be between 1 Myr and 8 Myr with the most likely value at ∼3 Myr (filled circle). The mass of S Ori 55 is $0.012 \pm 0.004 \, M_{\odot}$ for $\log L/L_{\odot} = -3.08$ (horizontal dotted line).
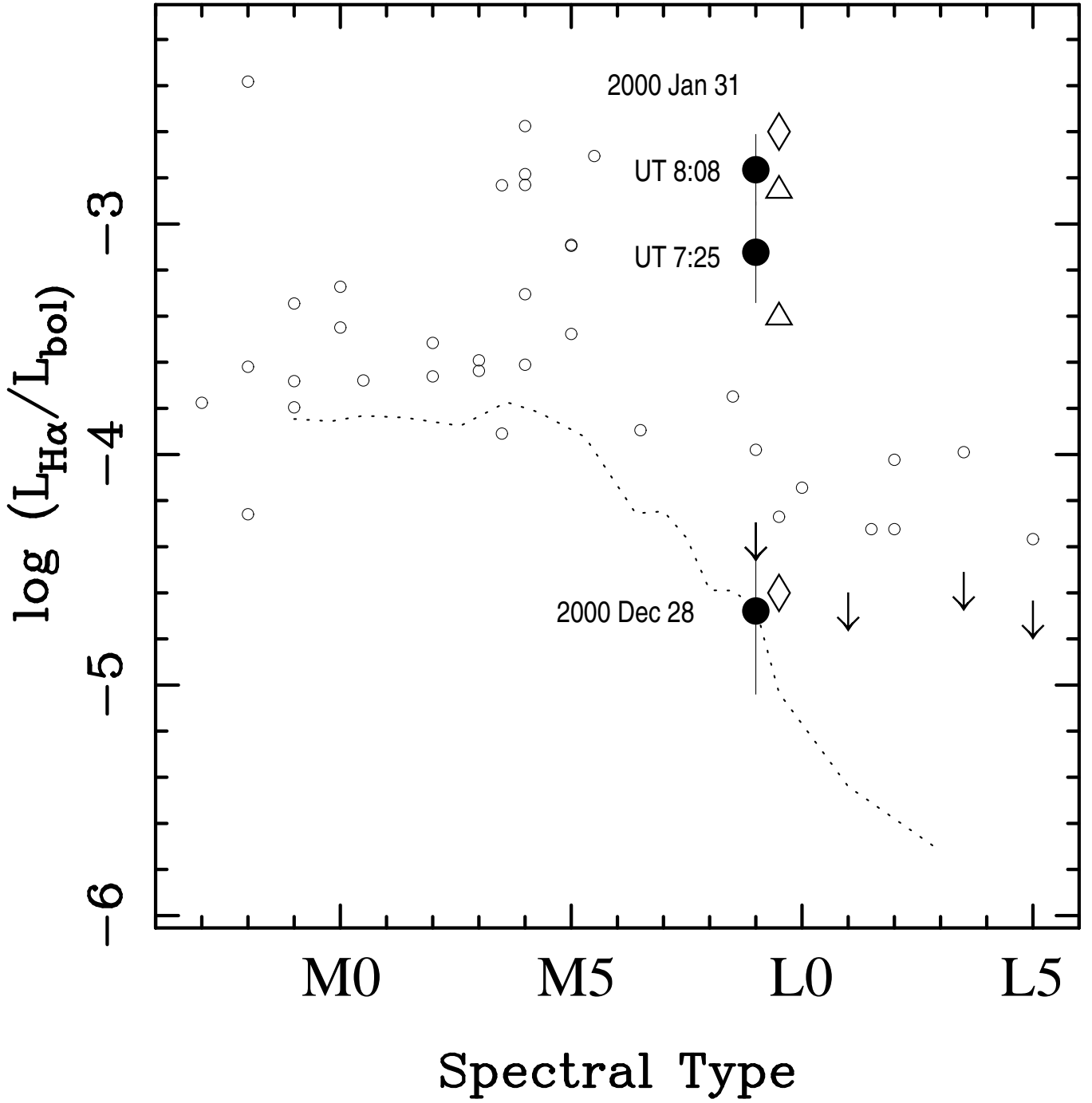
FIG. 4.— Ratio of Hα luminosity of the object to its bolometric luminosity as a function of spectral type. σ Orionis members are plotted with open circles, and S Ori 55 is indicated with filled circles. The star–brown dwarf boundary in σ Orionis takes place at around the M5 spectral type, and the brown dwarf–planetary-mass frontier at around the M9 class. The averaged locus of field stars is delineated by the dotted line. Ratios of PC 0025+0447 (triangles, minimum and maximum Hα emissions found in the literature) and 2MASSW J0149090+295613 (diamonds, quiescent and flaring stages) are also plotted.